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MAGNETISM IN METEORITES

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ABSTRACT

We present here a somewhat simplified overview of the subject of magnetism in meteorites. A glossary of magnetism terminology followed by discussion of the various techniques used for magnetism studies in meteorites is included. The generalized results from use of these techniques by workers in the field is described. A brief critical analysis is offered.

I. INTRODUCTION

The science of meteoritics is unique, not only in its diversity within a discipline, but in its diversity of disciplines as well. Anyone engaged in meteorite research soon becomes painfully aware that the types of studies conducted on meteorites cover a vast range of subjects. From discussions with our colleagues, we gathered that the field of meteorite magnetism is an area relatively unknown to many meteoriticists. This paper is our attempt to introduce the subject in a fundamentally simple and hopefully a scientifically reasonable manner. Furthermore, in our attempt to describe the nature of the magnetic studies conducted on meteorites and the magnetic record preserved in meteorites we present a review as well.

Presently all techniques employed in meteorite magnetism research have been adopted virtually unchanged from terrestrial paleomagnetism. In terrestrial magnetic studies, however, the primary emphasis is placed on determining the direction, rather than the intensity, of the earth's magnetic field in the geological past. As directions in meteorites are arbitrary (except within a single meteorite specimen), the primary goal of meteorite magnetism studies is to determine the intensity of the magnetic fields prevailing in the early solar system. In this paper we will restrict our discussion to magnetic techniques applied to meteorite research.

II. GLOSSARY OF MAGNETISM TERMINOLOGY

The magnetization observed in meteorites is a complex phenomenon which depends upon (1) the intensity of the magnetic field(s) to which the meteorite or its mineral phases was exposed, (2) the temperatures to which the meteorite was subjected, particularly during and after exposure to magnetic fields, (3) the magnetic minerals in the meteorite, and (4) the processes by which the minerals became magnetized. Following the initial recognition of the potential of studies of terrestrial rock magnetism [see, for example, Chevallier (1925); Mercanton (1926); Matuyama (1929)], notable progress has been made in understanding the processes by which rocks (and later on, partially by analogy, meteorites) may become magnetized. To foster more complete understanding of the processes, numerous laboratory techniques have been developed through the years to help resolve the complex magnetization record stored in the sample and thereby release new information concerning physical processes operating in the early solar system.

Virtually all the magnetism in meteorites is carried by magnetite and nickel-iron alloys although other minerals such as schreibersite and magnetic sulfide phases may also contain significant information. The identification and study of minor magnetic mineral components in meteorites is an area which has not been investigated to any extent.

Any grain of a magnetic mineral is said to consist of one or more magnetic domains. Sufficiently small grains ($\sim 10^2$ Å) can be regarded as single domains. Separating the domains are domain walls which may be considered as magnetic energy barriers. For a given magnetic mineral within a particular sample, the intensity of the magnetization per unit volume is the same in all domains although the directions of the magnetization are not necessarily the same.

In the absence of an applied external magnetic field, the direction of magnetization of each domain of a magnetic mineral will be preferentially oriented along one of several axes which is determined by the shape of the grain and/or by the crystalline anisotropy of the mineral. In an applied magnetic field the direction of the magnetization of a domain will be changed in such a way that it will tend toward alignment with the direction of the applied field. If the magnetic field is relatively weak, the direction of magnetization of the domain will reversibly return to its initial preferred direction after removal of the external field. Such reversible magnetization is termed induced magnetization. If however, the energy supplied by the applied field is greater than the magnetic energy barrier of the domain, the direction of magnetization of the domain will not return to its preferred position when the applied field is removed. This is remanent magnetization, (NRM), the coercive force being defined as the value of the applied field when the irreversible transformation takes place.

If a meteorite specimen is allowed to remain at room temperature in a sufficiently strong magnetic field, it may acquire a remanent magnetization in the direction of the applied field provided that the field is larger than the lowest coercive force of its magnetic minerals. This is called isothermal remanent magnetization (IRM).

If the magnetic field is weaker than the lowest coercive force of the magnetic minerals present and if the meteorite specimen remains for a long period of time in some fixed orientation with respect to the direction of the field, the weak field will effect a bias on the normally random thermal agitation which may allow the magnetization of the domains to cross over energy barriers otherwise unexpected in such a weak field. This magnetization is acquired slowly and, when the applied field is removed, the magnetization of the domain will reversibly return to its initial preferred direction on a time scale comparable to its acquisition. This is viscous remanent magnetization (VRM).

Aside from the effects caused by an externally applied magnetic field on the magnetization of a mineral such as described above, one must consider the effect of temperature on the magnetization. If a magnetic mineral, carrying a remanent magnetization is heated, the thermal energy increases until it equals the magnetic barrier energy at which point the magnetic moments become randomized. The temperature at which this occurs is characteristic of the particular mineral involved and is called the Curie point or Curie temperature. If a magnetic mineral cools through its Curie point in the presence of a magnetic field, at the Curie temperature it begins to develop a magnetization in the direction of the applied field. This magnetization, for weak fields comparable in magnitude to the earth's field, is proportional to the intensity of the external field. This is an important characteristic which allows estimation of the magnetic field intensities in the early solar system. A magnetization acquired as the mineral cools through its Curie temperature is called thermal remanent magnetization (TRM).

If a magnetic mineral is heated to some temperature below the Curie temperature, then cools in a magnetic field, a partial thermal remanent magnetization (PTRM) forms. Reheating the mineral in the absence of an external field will cause the magnetization to disappear in the same temperature range that it was acquired. Thus a PTRM preserves a faithful memory of the temperature and external field which initially caused the acquisition of the PTRM. This is an important characteristic of thermal demagnetization analysis which may allow estimation of paleotemperatures in some meteorites.

Chemical changes taking place in the presence of an external magnetic field can cause newly created magnetic mineral grains to grow in alignment with the direction of the applied field and acquire a magnetization. This is termed chemical remanent magnetization (CRM) and may take place for either non-magnetic or magnetic minerals undergoing reactions at low temperatures which change them to different magnetic minerals. The character of this magnetization is virtually indistinguishable from a TRM. If sufficient heating is involved a combined TRM and CRM may result. This is thermochemical remanent magnetization (TCRM).

If the low temperature compaction of a meteorite such as a carbonaceous chondrite were to involve very small grains which had previously acquired a TRM, it is possible for these grains to become aligned with any external magnetic field operating at the time. This could lead to a net magnetization of the compact body, called *depositional remanent magnetization* (DRM). Since the grains originally had a TRM, the DRM described above would have the characteristics of a TRM. The relative stabilities of the different types of remanent magnetization discussed above are $\mathrm{VRM} < \mathrm{IRM} < \mathrm{TRM} = \mathrm{CRM} = \mathrm{DRM}$.

All the above types of remanent magnetization are generally acquired in weak magnetic fields (~0.5 Oe). This should be distinguished from laboratory induction in very large fields (~1000 Oe or greater) which results in *saturation magnetization*, (J_s). The temperature dependent behavior of the force of attraction between the magnetic components in the meteorite sample and a very strong magnetic field (displayed graphically in a J_s-T plot) forms the basis for thermomagnetic analysis (discussed below).

III. MAGNETIC TECHNIQUES AND RESULTS

It is convenient for purposes of discussion to divide magnetic studies into two catagories: (1) Those studies based on the magnetic properties of meteorites, and; (2) those studies based on the observed remanent magnetism of meteorites and aimed specifically at estimating the intensity of magnetic fields in the early solar system. This division is somewhat artificial in practice as these studies are by nature complementary. Historically, the second catagory evolved from the introductory work of Stacey and Lovering (1959) and Lovering (1957), whereas some studies classified under (1) above considerably predate work based on natural remanent magnetism. For example, on the basis of magnetic susceptibility measurements, Cloetz (1864) determined that magnetite was present in the Orgueil meteorite, metallic iron being absent. The comprehensive early work of Smith (1908) layed a solid foundation for understanding the temperature magnetic transformations in the Ni - Fe system. Upon this foundation Smith and Young (1939) utilized a technique termed thermomagnetic analysis to measure the nickel content of taenite *in situ* in iron meteorite samples. As this is of importance in recent meteorite research, we will discuss it in some detail.

A. THERMOMAGNETIC ANALYSIS

It should be emphasized that this technique does not deal directly with the question of magnetic fields in the early solar system. Rather, it is useful for the identification of the magnetic components present in meteorite samples and for determining the degree of alteration of the magnetic phases during laboratory heating. The latter aspect is of particular importance as all techniques presently known for estimating magnetic field intensities from the remanent magnetization of a meteorite sample are variants of the Thellier technique (discussed in section C) and involve heating of the meteorite sample.

In principle the thermomagnetic technique is deceptively simple. A sample of meteorite material (whole rock or crushed) is suspended from a sensitive balance.

Application of a large (~3kOe), inhomogeneous magnetic field to the sample results in a force of attraction (Faraday effect) between the magnetic components in the sample and the magnetic field. This force of attraction causes the balance to record an apparent weight which is many times that of the actual sample weight. The weight recorded depends on the specific magnetic components present and the respective amount of each present in the sample. For example, 1 mg of metallic iron would appear to weigh about 230 mg with application of the magnetic field. Similarly, 1 mg of magnetite (Fe_3O_4) would appear to weigh about 95 mg. This apparent weight is effectively a measure of the saturation magnetization. For any given magnetic mineral, the saturation magnetization is temperature dependent - diminishing with increasing temperature until it essentially vanishes at the Curie point. Thus, heating the sample while applying the magnetic field causes the apparent weight to decrease with increasing temperature. At temperatures above the highest Curie temperature of the magnetic components in the sample, the apparent weight is virtually identical to the real sample weight.

Stacy *et al*. (1961) quantitively ascertained the magnetite content of the Mokoia chondrite utilizing thermomagnetic analysis. Recently Larson, *et al*.(1974a), Watson, *et al*. (1974), and Herndon, *et al*. (1974) determined the magnetite content of almost all the known carbonaceous chondrites using this technique. Although thermomagnetic analysis is used routinely in magnetic studies for the identification of magnetic phases, there are indications that the application of variations on this technique may yield significant information for meteoriticists. For example, Lovering, et al. (1960) employed this technique in a novel application to determine the thickness of reaction rims resulting from ablation heating in two nickel-rich ataxites. This data, coupled with microscopic observation of thermal effects and theoretical calculations, permitted estimation of ablation mass loss in these meteorites. As mentioned previously, Smith and Young (1939) demonstrated the potential of this technique for determining the nickel content in meteoritic metal. Lovering and Parry (1962) employed a similar, though much improved, technique to measure the nickel content of iron meteorites.

Fig. 1 shows a typical saturation magnetization vs. temperature (J_s-T) curve for a meteorite sample containing a single magnetic component, magnetite. Note that the saturation magnetization decreases slowly with increasing temperature until near the Curie temperature (~580°C for magnetite) at which the magnetization drops rapidly to a negligible value. Multicomponent systems show inflections representative of the temperatures at which the magnetic moments vanish for each phase. Such behavior is diagnostic, leading to the identification of the various magnetic constituents present. Fig. 2 illustrates this behavior for a meteorite sample containing magnetite and metallic iron (Curie temperature 770°C).

Lovering and Parry (1962) first demonstrated the utility of the thermomagnetic technique for the qualitative identification of the magnetic phases present in meteorites. Some subsequent studies (Banerjee and Hargraves, 1972; Butler, 1972; Gus'kova, 1963, 1965a,b; Weaving, 1962a) incorporated the thermomagnetic analysis technique solely for the qualitative identification of the magnetic phases present in meteorite samples.

From the standpoint of paleointensity studies, thermomagnetic analysis provides a convenient method of assessing the extent of alteration of the magnetic phases in a meteorite sample during laboratory heating. The reversibility of the J_s-T curves shown in Figs. 1 and 2 (i.e. the near coincidence of the heating and cooling paths) attests to minimal oxidation of reduction of the magnetic phases. Since the saturation magnetization of $Fe > Fe_3O_4 > Fe_2O_3 > FeO$, any change in the relative proportion of these phases resulting from oxidation or reduction during the experiment would be reflected by an irreversible behavior of the J_s-T curves. The recent adaptation of a gas mixing system for control of the oxygen fugacity during heating offers considerable improvement over the previously employed methods of heating under vacuum or in an inert atmosphere (Larson, <u>et al</u>. 1974b). Unfortunately, even carefully controlling the oxygen fugacity to maintain metallic iron and/or magnetite in their respective stability fields during laboratory heating, is not in itself a panacea. Stacey, et al. (1961) and Lovering and Parry (1962) determined thermomagnetically that troilite can readily undergo oxidation (forming magnetite) even under vacuum. For magnetic studies on ordinary chondrites, where the NRM is carried by metallic iron, this problem may be of minor consequence. But for some carbonaceous chondrites, such as Murchison, the formation of magnetite from the oxidation of troilite during thermal experiments poses major problems. Fig. 3 shows a saturation magnetization vs. temperature curve for a sample of the Murchison meteorite. It is evident from inspection of the figure that the saturation magnetization observed on the cooling cycle is greater than on the heating cycle. The J_s-T curve is characteristic of magnetite (for comparison refer to fig. 1); the variable shape of the heating curve attests to the formation of intermediate alteration phases (Watson et al. 1974). Note that although there is no apparent change in saturation magnetization while the sample is kept at ~585°C, magnetite is being produced rapidly as evidenced by the large increase in saturation magnetization upon cooling as the sample dropped to temperatures beneath the Curie point of magnetite. Similar though less prominent behavior was noted in Murchison by Banerjee and Hargraves (1972). The increase in saturation magnetization in the Murchison sample and in eleven other carbonaceous chondrites including Allende is prominent due to the apparent absence of magnetic minerals other than sulfide phases (Herndon et al. 1974). It is not known whether the oxidation of troilite can be inhibited by controlling the sulfur fugacity during heating by either an appropriately chosen gas mixture or a solid state buffer system.

B. ALTERNATING FIELD DEMAGNETIZATION

Unlike thermomagnetic analysis alternating field demagnetization (and the following techniques discussed in the remainder of this paper) deal directly with the remanent magnetization observed in meteorites. Since the total permanent magnetization in a meteorite is frequently the resultant of a combination of components (isothermal and viscous in addition to the more stable components), and since some of these components (IRM and VRM) are most frequently only a complication in the study of the more stable magnetization in the early solar system, it is desirable to remove those nuisance components prior to more extensive thermal demagnetization experiments. This can be accomplished quite simply by subjecting the sample to an alternating magnetic field (Banerjee and Hargraves, 1971; Butler, 1972; Brecher, 1972; Gus'kova, 1963; Larson, et al., 1973; Weaving, 1962a).

Fig. 4 shows that the relative stability of isothermal remanent magnetization (IRM) to alternating field demagnetization is quite low compared with that of thermal remanent magnetization (TRM). Viscous remanent magnetization (VRM), which is not shown in Fig. 4, is generally even less stable to a.f. demagnetization than IRM. Thus it can be seen that as the intensity of the alternating field is increased, the less stable components (IRM and VRM) are erased selectively to a much greater extent than the more stable components (TRM or CRM, etc.) which are of importance in recording the magnetic field acting on the meteorites early in their history. Furthermore, by noting relative change in intensity of the magnetization during a.f. demagnetization it is possible to gain some insight into the stability and nature of the natural remanent magnetization (NRM). Because the NRM of meteorite samples is generally a combination of soft (IRM and VRM) and hard (TRM) components, additional information can be gained by noting relative changes in the direction of the magnetization vector. The NRM is the vector sum of all of the components of magnetization. The directions of these components are not generally the same. As the soft (less stable) components are erased, their contribution to the direction of the resultant magnetization vector will be removed and the NRM vector may change in direction, ultimately yielding the direction of the resultant magnetization rector of the hard (more stable) components. A single stable component yields a constant direction, whereas a multicomponent system results in directional change during the course of the demagnetization.

The ability of a meteorite sample to acquire a soft magnetization (IRM or VRM) depends in part on the relative coercivities of its magnetic minerals. Erratic behavior during A.f. demagnetization may be indicative of minerals with low coercivities which may readily acquire a magnetic moment at ambient temperatures from the earth's magnetic field. Such behavior can be demonstrated by storage tests. If a meteorite sample is a.f. demagnetized (say to 100 Oe), allowed to remain in the earths field for several days and remeasured, then a change in intensity and/or direction of the magnetization vector would indicate that the meteorite sample contains magnetic minerals of low coercivities which can readily acquire a magnetic moment from the earth's magnetic field. Again demagnetizing (to 100 Oe) would erase the newly acquired soft component and allow recovery of the direction and intensity that the sample had after the initial demagnetization at 100 Oe. This technique is useful to gain some insight into the character of the NRM - its nature, direction, stability and number of components. This information is important in considering which samples should be sacrificed to further (destructive) studies such as thermal demagnetization.

Alternating field demagnetization is a technique used routinely in virtually all magnetic studies for one reason or another. For example, Brecher (1972) employed a.f. demagnetization in a variant of the Thellier technique for paleointensity estimates (see sections C and H). Alternating field demagnetization is a non-destructive technique (except as it alters the magnetization and as such it is ideally suited for preliminary investigations to ascertain which meteorite specimens should be subjected to further destructive studies such as thermal demagnetization.

C. THERMAL DEMAGNETIZATION

In their classic work Thellier and Thellier (1959) demonstrated that a partial thermal remanent magnetization (PTRM) obtained in a weak field (<10 Oe) developes a memory characteristic with regard to heating, i.e., a rise in temperature from t_2 to t_1 destroys precisely that portion of the magnetization which developed during the original cooling period within the same temperature interval from t_1 to t_2. They further demonstrated that for experiments conducted in weak fields comparable in magnitude to the earth's magnetic field (~0.5 Oe), there exists a linear relationship between the loss of magnetization in a given temperature interval during laboratory reheating conducted in field free space and the acquisition of magnetization obtained cooling through the same temperature interval in a magnetic field of known intensity. This linearity permits estimation of the intensity of the magnetic field responsible for the initial implantation of the PTRM. At the present time, all methods of paleointensity estimation are based on the Thellier technique or some variant thereof. The validity of this technique is subject to the following restrictions: 1) that the NRM is either PTRM or TRM in character (as opposed to, say, a depositional remanent magnetization) and, 2) that the magnetic phases of the meteorite samples undergo no significant alteration during laboratory heating. The difficulty in insuring that no significant alteration occurs has rather severely limited the application of this technique to meteorite samples.

Stacey, et al. (1961) first utilized thermal demagnetization techniques in meteorite studies, estimating paleointensities for the Mt. Browne and Farmington chondrites. Although some troilite was converted to magnetite upon heating in Farmington and the magnetization of Farmington was generally somewhat unstable, values for the paleointensity of the field were estimated to be 0.25±0.08 Oe and 0.18±0.09 for Mt. Browne and Farmington, respectively.

The next estimate of the intensity of the field(s) producing the magnetization in meteorite parent bodies was by Weaving (1962a). In his thorough study of the magnetic properties of the Brewster chondrite, the thermal demagnetization technique was utilized to estimate a paleofield intensity of 0.1 Oe, probably not significantly different from the two estimates of Stacey, et al. (1961). Again the main magnetic phase was attributed to metallic iron so that the potential difficulty with troilite oxidation was apparently not a serious problem.

Guškova (1963) followed soon after with paleointensity determinations of ~0.2 Oe for five chondrites (again with metallic iron as the principal magnetic component). Later Guškova (1965a) also reported similar analyses on three irons and a stony-iron. No other attempts at estimating paleointensities were made until Banerjee and Hargraves (1972), Brecher (1972), and Butler (1972) conducted their studies on several carbonaceous chondrites. Values of about 1 Oe were obtained. These latter three experiments are discussed further in section H.

D. MAGNETIC ANISOTROPY

Stacey, et al. (1961) were also first to report that meteorites exhibited magnetic anisotropy - resulting from alignment of elongated metal grains. Weaving (1962a,b) followed with the observation that every sample of seven chondritic meteorites he studied had anisotropic magnetic susceptibilities and confirmed that in the Arapahoe meteorite, at least, the grains were generally elongated and their long axes were predominately aligned in the direction of maximum susceptibility.

In contrast to Stacey, et al.'s (1961) observation that the Mokoia carbonaceous chondrite showed little or no magnetic anisotropy, Brecher (1972) reported "stronger anisotropies in the carbonaceous chondrites than ever seen previously in terrestrial rocks or chondrites." Interestly she observed that both the anisotropy and the degree of lineation increased after removal of the soft remanence by cooling-cycling so that the anisotropy is apparently associated with the stable remanence. (See next section for discussion of the cooling-cycling technique). Presently the origin of the anisotropy is not clear but illucidation of this process will certainly be a significant addition to our knowledge of the origin of meteorites. Unfortunately, one cannot presently say whether the grains were aligned magnetically or by some other process. Since the natural remanence is not in the direction of easy magnetization in the chondrites studied by Weaving (1962, a,b) magnetic alignment appears doubtful.

E. LOW-TEMPERATURE CYCLING

An alternative to removing unstable magnetic components by thermal or a.f. demagnetization was suggested by Ozima, et al. (1964) and has been used on meteorites only by Brecher (1972). This method simply involves cooling a sample in nonmagnetic space to a temperature below -120°C, and cycling across the magnetocrystalline anisotropy transition of magnetite. Single-domain magnetite grains, which generally appear to hold the bulk of the stable remanence of that phase, are apparently unaffected by the low-temperature cycling. Multidomain magnetic phases carrying soft nuisance components are effectively "cleaned". Remanence carried by metallic iron and/or magnetic sulfide phases is unaffected by low-temperature cycling. Some inferences regarding relative grain sizes may be made from cooling-cycling data when coupled with petrologic or thermomagnetic identification of the magnetic phases present in meteorite samples.

F. COERCIVE FORCES

The force (a D.C. magnetic field) required to reduce the natural remanent magnetization to zero is the coercive force, and is generally considered to be a measure of the stability of the remanence. A high value for the coercive force indicates high stability, although a low value does not necessarily mean that small stable components are absent. Guškova (1963) found the coercive force in chondrites to be ~20 Oe. Banerjee and Hargraves (1971) and Brecher (1972) found considerably higher values of ~100 to > 350 Oe for the carbonaceous chondrites and attributed the higher coercivities in carbonaceous chondrites to sub-micron particles of the magnetic phases. In all three studies, stable remanence was indicated.

G. NATURAL REMANENT MAGNETIZATION AND SUSCEPTIBILITY

During the 1960's the Russians, primarily Gus'kova and Pochtarev, systematically measured the NRM and susceptibilities of almost all the meteorites in USSR collections. The Russian work on magnetism was reviewed in this Journal and will not be elaborated on here (Herndon, et al., 1972).

Weaving (1962a) conducted a study of the Brewster chondrite in which samples of the NRM were taken as a function of distance across a face of the meteorite and found large increases in the NRM very near the fusion crust surfaces. Fig. 5 illustrates the results found by Weaving. Stacey (1967) suggests that since the process of ablation seems to generate a strong local magnetic field near the edge of the meteorite, but not at the center, "the only field of this form is a toroidal one, which might have been generated thermoelectrically within the surface layer if the surface became electrically conducting at elevated temperatures, or more probably was generated by potential differences due to the ablation process itself, with the conducting path completed in the surrounding plasma".

H. PALEOINTENSITY DETERMINATIONS - LIMITATIONS

We have already mentioned briefly several attempts to estimate the intensity of the magnetic field(s) responsible for the observed remanent magnetism in various meteorites. For ordinary chondrites, stony-irons and irons, metallic iron appears to be the dominant magnetic phase. Paleointensity estimates on these meteorites (0.1 to 1 Oe) should be reliable, provided the metallic iron was a primary mineral phase and that the NRM was acquired as the meteorite cooled. There is no evidence to the contrary.

In 1972, three attempts were made at estimating paleointensities from data on several carbonaceous chondrites. Banerjee and Hargraves (1972) and Butler (1972) employed a step-wise variant of the Thellier technique of thermal demagnetization followed by remagnetization in a field of known intensity. This procedure was repeated at successively higher temperatures. Brecher (1972) used a single step variant of the Thellier technique which involved heating the sample in argon to a temperature of 150-250°C and allowing the sample to cool in a known field (thus acquiring a PTRM). The a.f. demagnetization of this PTRM was compared with the previously determined a.f. demagnetization of the NRM. The different choices of experimental technique employed by the above mentioned workers led to different interpretations of their data. Banerjee and Hargraves (1972) and Butler (1972) recognized from their data that at temperatures above 90-130°C "physico-chemical changes" occurred. Therefore they utilized only their low temperature data for paleointensity estimates. Brecher (1972) found that her data on Allende, Murchison, and Murray did not extrapolate to zero (as expected from a single component TRM) and suggested the "presence of one or several (preaccretionary?) CRM components". It is significant that her data on Renazzo did extrapolate to zero. From our thermomagnetic studies (Larson et al. 1974a; Watson et al. 1974; Herndon, et al. 1974) it appears likely that the "physico-chemical changes and the "non-zero extrapolation" discussed above resulted from the oxidation of troilite during laboratory heating. Banerjee, Brecher, and Butler (personal communication) have stated that their data shows the reverse of the effect expected from the simple addition of magnetite during the experiment. However, additional studies (D. E. Watson, personal communication) suggests that at early stages in the formation of magnetite from the oxidation of troilite (in a known magnetic field) the magnetite developes a magnetization antiparallel to the direction of the applied field (i.e. magnetic reversal). If confirmed this would explain the ambiguities mentioned above. The paleointensities determined for the five carbonaceous chondrites studied ranged from 0.2-2.0 Oe, values not significantly different from those found for ordinary chondritic, stony-iron, and iron meteorites.

The magnetization of carbonaceous chondrites may be more difficult to interpret than that of other meteorite classes. The possibility that chemical reactions (CRM) or depositional effects (DRM) either altered or contributed to their magnetization is enhanced by the extremely fine-grained mineralogy of these meteorites. The fundamental problem involved reduces to one of establishing the validity of applying the Thellier technique to carbonaceous chondrites. The observed remanent magnetism of these meteorites strongly suggests that magnetic fields of significant intensity were present in the early solar system at some time during their development. Much more work is required before we can hope to illucidate with reasonable certainty the origin, intensity, and duration of these fields.

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Fig. 1. Saturation magnetization as a function of temperature (J_s-T) curve for the Cl chondrite Alais (Larson, etal. 1974). Magnetite is the only magnetic mineral indicated as evidenced by the shape and Curie temperature of a 580° C. The near coincidence of the heating and cooling curves indicates that insignificant alteration of the magnetite has occurred by heating the sample (~1 mg) of Alais.

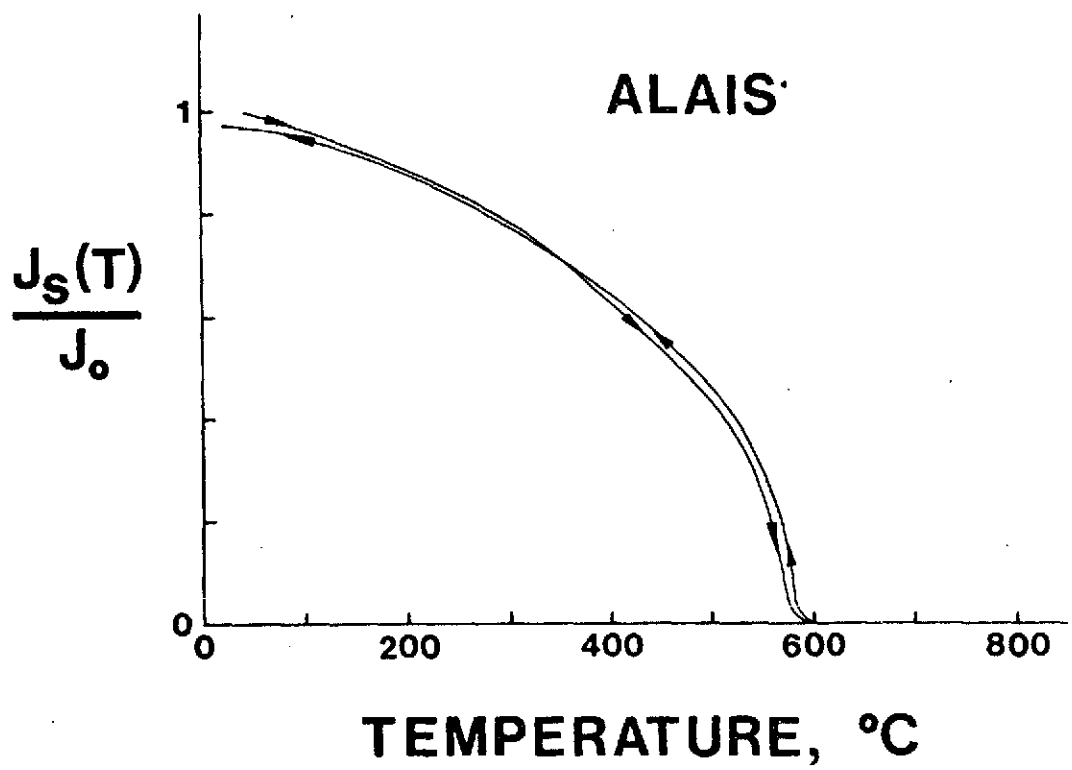


Fig. 2. Saturation magnetization as a function of temperature (J_s-T) curve for the ureilite Novo Urei (our unpublished data). Both magnetite and iron are indicated as principal magnetic minerals as evidenced by the inflection point in the curve at about 580°C (indicating magnetite) and the extension of the curve on out to about 770°C, the Curie temperature of iron. Once again, the near coincidence of the heating and cooling curves indicates that neither the iron nor the magnetite have been significantly altered by the heating of the Novo Urei sample to ~800°C.

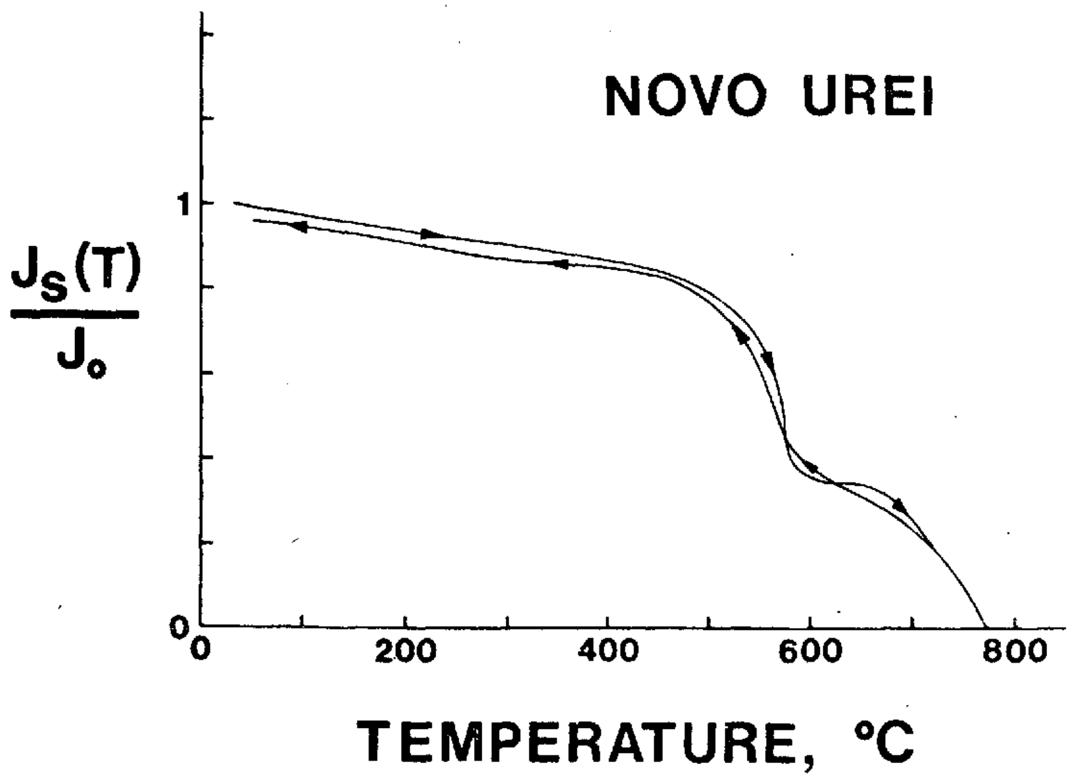
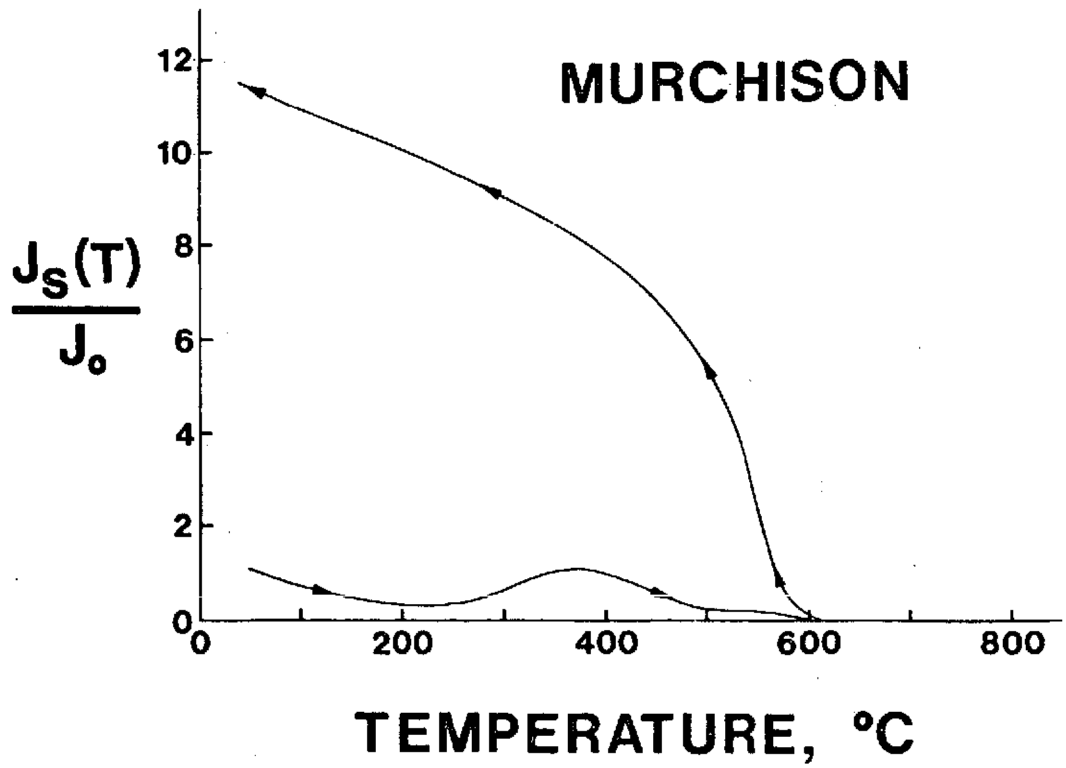


Fig. 3. Saturation magnetization as a function of temperature (J_s-T) curve for the C2 Chondrite Murchison (Watson, etal. 1974). Note that whereas the heating portion of the curve is not at all similar to the behavior expected for magnetite, the cooling curve is quite similar to Fig. 1. Apparently some material (either non- or weakly magnetic) was thermally altered to magnetite. No iron is indicated as the curve was at zero by about 600°C.



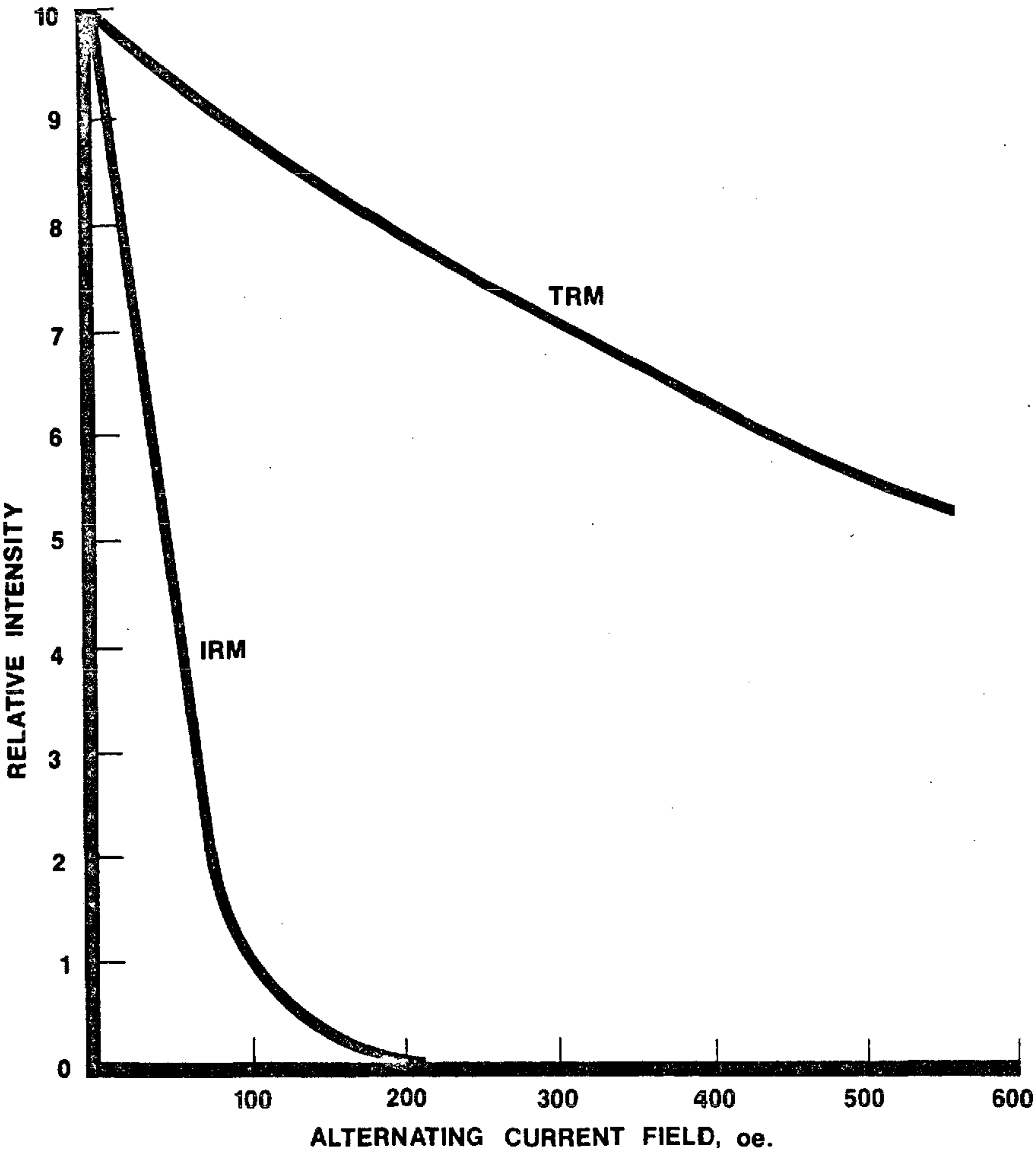


Fig. 4. Schematic relative intensity plot of alternating field demagnetization of the stable thermal remanent magnetization compared with the unstable isothermal remanence magnetization. Notice that most of the isothermal remanent magnetization is removed by a relatively mild a.f. demagnetization, e.g.30 Oe, whereas the thermal remanent magnetization is almost unaffected.

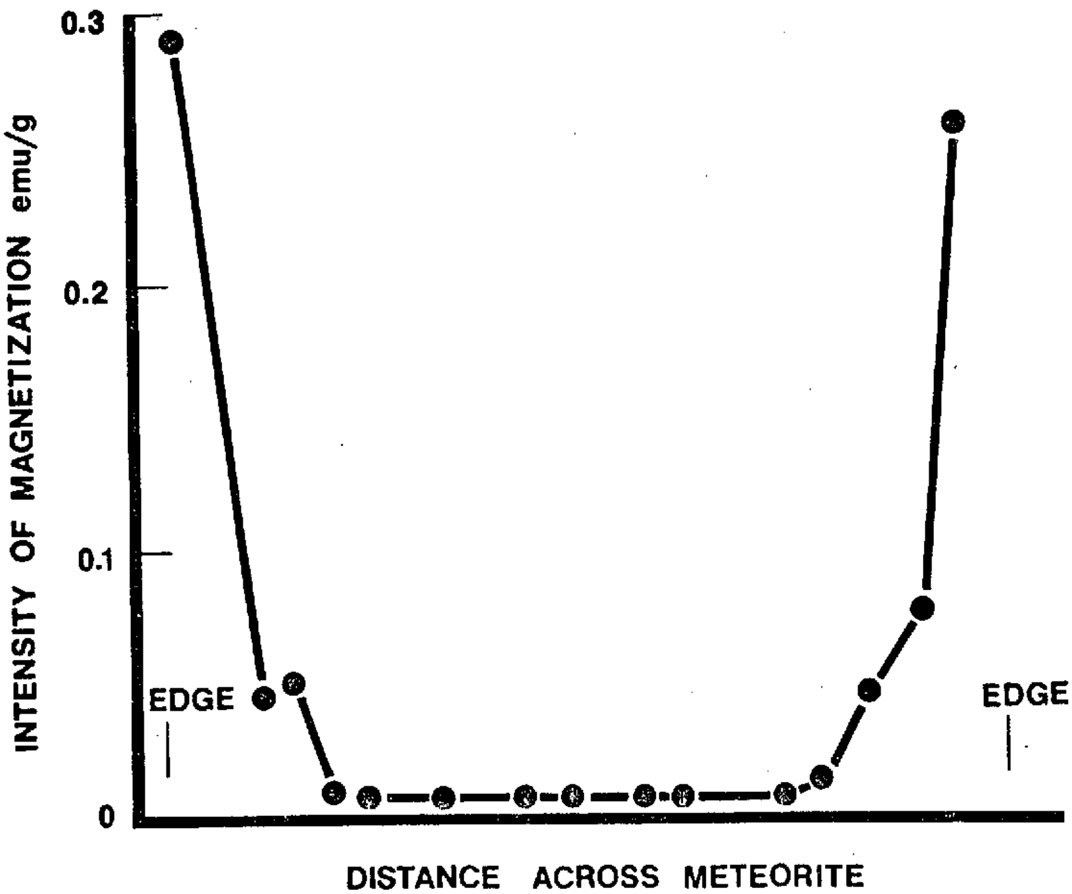


Fig. 5. Variation of natural remanent magnetization intensity as a function of distance across the face of the Brewster meteorite (Weaving, 1962a).